

Development of a Prototype Real-Time Automated Filter for Operational Deep Space Navigation

by C. Masters[†] and V. M. Pollmeier^{††}

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

Abstract

Operational deep space navigation has in the past, and is currently, performed using systems whose architecture was originally designed to accommodate tape data transfers and computing environments with a tiny fraction of the current capability. Additionally, this architecture requires constant human supervision and intervention. A prototype for a system which allows relatively automated processing of radio metric data received in near real-time from NASA's Deep Space Network (DSN) without any redesign of the existing operational data flow has been developed. This system can allow for more rapid response as well as much reduced staffing to support mission navigation operations.

Introduction

In the past and current practice, deep space navigation operations have been relying on a system architecture that was designed for tape data transfers. The entire navigational procedure consists of processing batches of observations to correct spacecraft initial conditions and then using the corrected initial conditions to regenerate spacecraft trajectory. This practice not only requires constant human intervention but also makes it impossible to process data in an automated fashion.

In certain operational scenarios, it is desirable to recursively process data as they become available and to obtain the most current improvement on spacecraft trajectory (vice the correction on the initial conditions). Since the current software system cannot serve this purpose, the development of the prototype system, which is dubbed the Real-Time Automated Filter (RTAF), is intended to fill this vacuum. The fundamental building block of RTAF is the extended Kalman filter [Ref. 1], which allows processing of data one at a time. The data driven feature of the system takes advantage of the architecture of the X-Windows Real-Time Display (XRTD) software [Ref. 2]. This system works recursively and each recursive step consists of the followings. A data point is first obtained and validated; then the spacecraft trajectory is propagated to the time corresponding to the data; and then the data point is used to correct the propagated spacecraft trajectory, which will be used for propagating the spacecraft trajectory when the next data point becomes available.

Interestingly, the Kalman Filter algorithm has been widely used and proven powerful in many data reduction applications including geo-satellite orbit determination. However, no utilization of any forms of the Kalman Filter has been documented in the literature of deep space navigation operations. This prototype, once developed fully, may be the first such application using the Kalman Filter.

[†] Member Technical Staff, Navigation Systems Section, Jet Propulsion Laboratory

^{††} Acting Technical Manager, Navigation Systems Section, Jet Propulsion Laboratory

Approach

In the RTAFC, the models for the spacecraft dynamics and measurements are a subset of what is in the operational orbit determination software in JPL. The spacecraft dynamics include the n-body point mass gravitational accelerations, solar radiation pressure with an assumed cylindrical spacecraft geometry, a limited oblateness perturbation, and accelerations due to maneuver motor burns of finite time length. The measurement models are J2000-ided to the coherent two-way Doppler with precision light time corrections for transmission and receiving times, as well as tropospheric delay of the radio signal. Filter parameters include the spacecraft state (position and velocity) and system parameters. Currently, the hydrostatic and wet zenith delays of the troposphere are treated as system parameters. Other examples of system parameters are solar radiation pressure and finite motor burn direction and duration.

Using the Extended Kalman filter modeling definition, the spacecraft dynamics are modeled by first order nonlinear stochastic differential equations, the system parameters by first order Gauss-Markov process, and measurements by discrete nonlinear equations.

$$\dot{\underline{x}} = f(\underline{x}(t), \underline{q}(t), t) + \Gamma(t) \underline{w}(t) \quad (1)$$

$$\dot{\underline{q}}(t) = A \underline{q}(t) + \underline{u}(t) \quad (2)$$

$$\dot{\underline{y}}(t) = B \underline{y}(t) + \underline{\beta}(t) \quad (3)$$

$$z(t_k^R) = h(\underline{x}(t_k^S), \underline{y}(t_k^R), t_k^I, t_k^K) + v(t_k^K), k = 1, 2, \dots \quad (4)$$

In above equations, \underline{x} is the spacecraft state vector; \underline{q} is the dynamic system parameters, such as solar pressure and maneuver parameters; \underline{y} is the ground system parameters, for example, the tropospheric zenith delays. For the measurement model, three times are involved, the station transmission time t_k^I , the station receiving time t_k^K , and the spacecraft transmission time t_k^S , all corresponding to the k-th data point. These times are related via precision time transformations between station time and ephemeris time as well as precision light time corrections. Statistical assumptions are the usual ones, such as the noise terms \underline{w} , \underline{u} , $\underline{\beta}$, and v are uncorrelated and are of mean zero. Data validation is a simple minded approach currently, which is to check that each raw data point lies within a specified deviation limit. Data outside of this limit is discarded.

The data flow from NASA's DSN to the navigation workstation is accomplished via the same interface as is used with the XRTD software system (Ref. 2). This system taps into the already existing radio metric information stream. Data flows from each DSN antenna to the Ground Communications Facility (GCF) located at JPL. From this facility, the data flows to VAX computers which serve the Radio Metric Data Conditioning team, a part of the DSN's Multi Mission Navigation Team at JPL. At this point, an auxiliary data stream is created which allows the tracking data to flow from this DSN computer through a gateway machine also controlled by the DSN to the navigation operations workstation. This gateway is connected via DECNET to the DSN VAX and via TCP/IP to the navigation workstation. The direction of the data flow is exclusively controlled from the secure DSN machines and is restricted to a limited set of operations machines. Additionally no direct contact between the DSN operations computer and project computers occurs. However, the result is that the navigation workstations receive the same Multi Mission Spacecraft Record (MMSPR) file that exists on the DSN computers with a time lag of no more than one minute. Figure 1 illustrates this data flow as well as highlights the software

processes and file manipulations that occur on each machine. Initially a process named *DSNLISTEN* receives incoming data and generates individual files of data blocks (DBF's). The *SPRCREATE* process creates individual spacecraft record files (SPR's) and multi mission spacecraft record files (MMSPR's) at a predetermined schedule which is defined via the human controlled process *SPRSCHEDULE*. The maximum frequency at which the MMSPR's are created is limited by the speed of the DSN Vax computer and is currently limited to once per two minutes. A process called *SPRNET* which runs on a DSN microVax monitors the MMSPR file on the primary machine and when it has been updated then transfers it to the navigation workstation via TCP/IP where a waiting process named *SPRD* receives the file and creates a copy of it on the navigation machine. The RTAF, then access the latest data from this file.

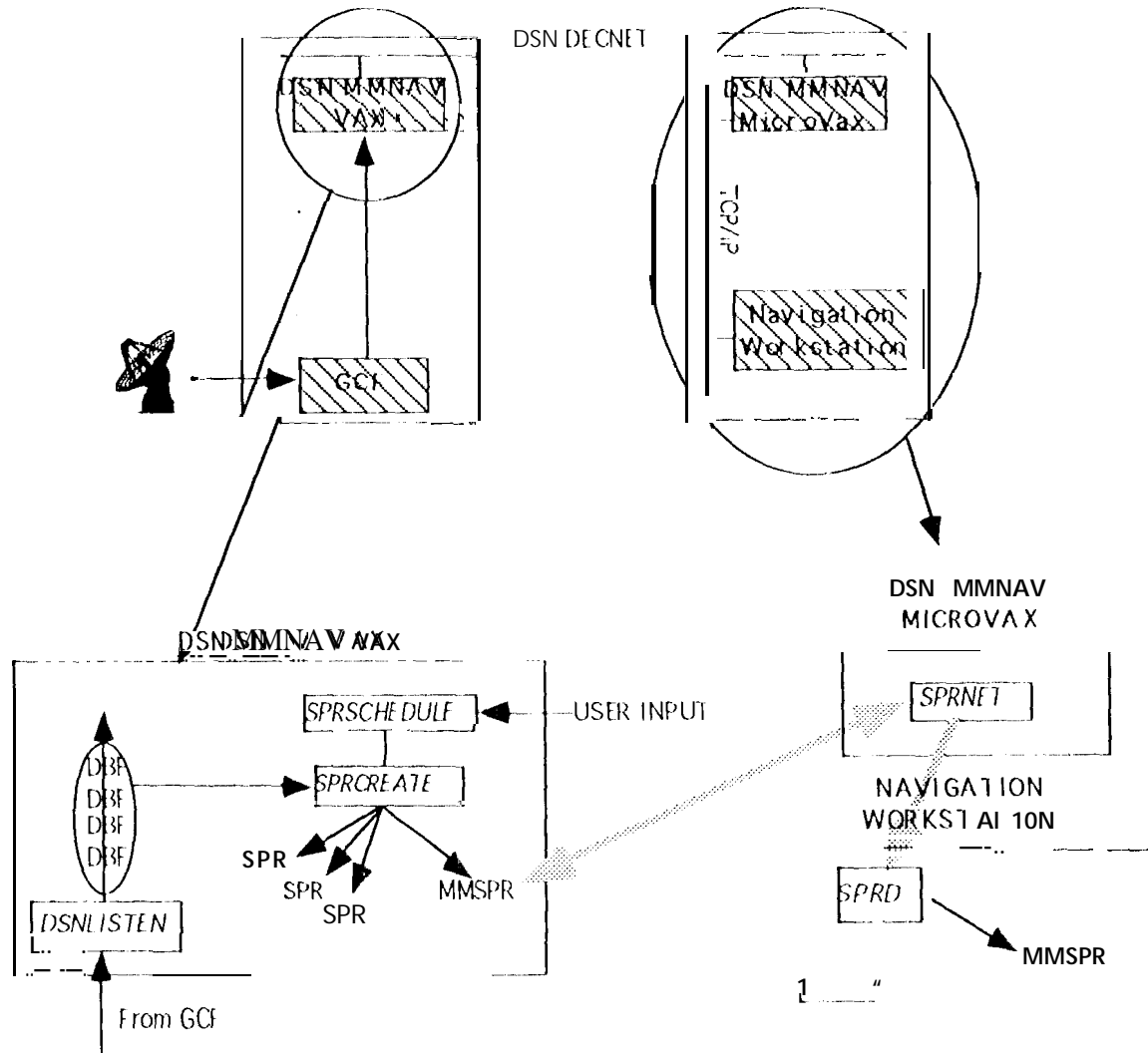


Figure 1: Network Data flow

As data flows in to the navigation workstation, the RTAF then recursively validates each data, extrapolates the spacecraft state and system parameters, computes predicted data using extrapolated state and system parameters, forms residual using the raw data and the predicted data, and corrects the extrapolated state and system parameters. The following structure chart of the RTAF depicts this recursive process.

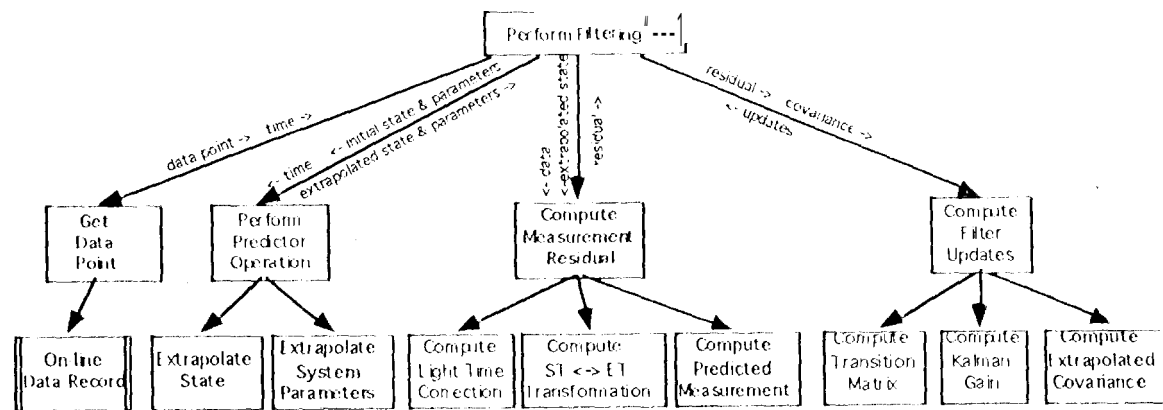


Figure 2: Filter Processing Algorithm

Conclusions and Future Plans

The RTAF represents a radically different way to perform deep space navigation operations. It has been shown to be well suited for real-time automated data processing, which would be impossible to accomplish using the traditional batch or batch sequential filter and it has high potential in autonomous navigation applications. In addition, it provides significant advantages over the traditional epoch state or pseudo epoch state formulations in its simplicity and extensibility as well as its natural way of modeling the temporal process.

Though this prototype has great promises, to be truly an operational tool, more work needs to be done. The future development will expand the spacecraft dynamic models and observable models. More sophisticated statistical methods will be incorporated in data and solution validation. Currently the system outputs a time history of changes in the estimated parameters. It is desired to have this system interface directly with one or more commercial numerical data analysis packages to allow greater data analysis capabilities. This prototype was developed in less than one year using parts of already existing systems. It is planned to develop a completely new operational tool based on this system design during the next eighteen months.

This new system will be similar in overall design to the one described here, but should provide much greater capabilities for autonomous operation as well as possible future application in on-board systems which do not use radio metric data types.

Acknowledgments

Special acknowledgment must be given to those who assisted in the development of this prototype including E. A. Rinderle, L. E. Bright, G. C. Rinker and T. P. McIlraith.

The research described in this paper was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States government or the Jet Propulsion Laboratory, California Institute of Technology.

References

- Chui, C. K. and G. Chen, (1991). *Kalman Filtering with Real-Time Applications*, 2nd ed., Springer-Verlag, Berlin Heidelberg.
- Pollmeier, V. M., (November 1992). XRTD: An X-Windows Based Real-Time Radio Metric Display and Analysis System, *Proceedings of Second International Symposium on Ground Data Systems for Space Mission Operations*, Pasadena, California.